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MODE LOCKED FIBER LASERS AND THEIR APPLICATIONS

KJT, Inc.

Kenneth J. Teegarden

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13. ABSTRACT *(Maximum 200 words)*
Mode locked lasers based on erbium and neodymium doped single mode optical fibers have been the subject of intense study for the past few years. The work performed under this effort was primarily driven by the need for efficient sources of short pulse radiation at 1.33 and 1.55 microns for broad band optical fiber communication systems. Work under this effort resulted in the design and fabrication of a new mode locked fiber laser prototype. By combining recent fiber grating technology with a unique quantum well saturable absorber, an erbium doped fiber laser operating with unusually low pump power and producing mode locked pulses of 10 picoseconds duration was fabricated. The laser is fiber integrated, rugged, and completely free of alignment and polarization sensitivity effects. The entire laser is enclosed in a 2x3x5 inch package.

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1.0 Introduction

Mode-locked fiber lasers which produce picosecond time-duration optical pulses at gigahertz repetition rates are ideal candidates for use in time-division multiplexed (TDM) optical interconnects. Presently, ultra-fast TDM is limited by the availability of a compact, short-pulse source that is compatible with fiber-coupled modulator technology. Fiber laser signal sources possess several significant advantages over the currently established diode laser technology:

1. The pulse widths achievable are significantly shorter, allowing a much greater potential use of the full bandwidth available from single mode fiber. Stable picosecond pulses are already in use and the femtosecond ranges are available when other components can utilize them.
2. The emphasis is on sources which are portable and free of excessive alignment and polarization sensitivity.
3. The wavelength and configuration are inherently compatible with fiber amplifier technology which facilitates compensation for distribution / splitting losses required in practical systems.
4. Soliton pulse generation and shaping can be formed naturally in a fiber laser, and can be optimized to minimize dispersion induced limits on signal propagation by using the nonlinear response of the fiber medium.

Mode locked lasers based on erbium and neodymium doped single mode optical fibers have been the subject of intense study for the past few years. This work has primarily been driven by the need for efficient sources of short pulse radiation at 1.33 and 1.55 μm for broad band optical fiber communications systems. Although ring cavities have been successfully used to construct mode locked lasers which produce sub picosecond pulses at these wavelengths, this configuration has proven to be extremely sensitive to stress and temperature induced birefringence and hence very difficult to stabilize.[1] On the other hand, fiber lasers based on linear, or Fabry-Perot, cavities are much more stable.[3-5] Fiber phase gratings with band widths of several nanometers and a continuous range of operating wavelengths are readily available for use as reflectors in such cavities and are compatible with mode locked operation with transform limited pulse widths of the order of picoseconds. One of the useful features of linear cavity lasers using a fiber grating as a reflector is that the wavelength of operation is determined by the center wavelength of the grating. Thus the laser output can be tuned over the entire gain curve by choosing different gratings. If the laser is mode locked and transform limited, the width of the output pulses may be determined by the band pass of the grating.[1] Thus it is, in principal, possible to construct a mode locked laser for which the operating wavelength and the pulse width can be selected simply be interchanging gratings or by tuning a single grating by the application of a mechanical stress or a temperature change.

Work under this contract has resulted in the design and construction of a new mode

locked fiber laser prototype. By combining recent fiber grating technology with a unique quantum well saturable absorber, an erbium doped fiber laser operating with unusually low pump power and producing mode locked pulses of 10 ps duration has been constructed. The laser is fiber integrated, rugged, and completely free of allignment and polarization sensitivity. The entire laser is enclosed in a 2x3x5 in. package. The cavity designs and components used in this laser are described below.

2.0 Results

2.1 Cavity Design

Two variations on a basic linear cavity design were evaluated as part of the development of the optimum system for a simple compact mode locked laser. These are shown in Figs. 1 and 2. In the first the laser is pumped via a conventional wavelength multiplexer with two input ports designed for the short wavelength pump radiation and the longer wavelength radiation emitted by the erbium doped fiber gain medium. The cavity is completed by fusion splicing a fiber grating to the long wavelength input port and butt coupling the output end of the erbium fiber to the multiple quantum well saturable absorber which serves as the second reflector in the linear cavity. The output of the laser is either taken through the fiber grating or through the saturable absorber itself. If the grating as the output coupler, because in this case the emitted radiation emerges on a single mode fiber which can readily be spliced directly into an external fiber system.The light emitted through the absorber must be collimated with an external optical element such as a grin rod or microscope objective. Thus the grating acts as fiber port while the saturable absorber acts as a free space port. It should be noted that both [ports can be utilized simultaneously. The fraction of light coupled out through either port can easily be varied by changing the grating reflectivity or the reflectivity of the saturable absorber with a dielectric coating.

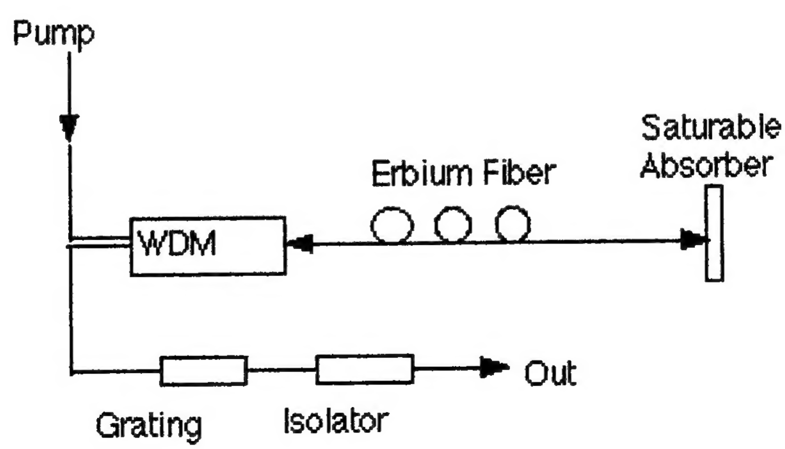

Fig. 1 Laser cavity utilizing a wavelength multiplexer.

In the second case, shown in Fig. 2, the erbium fiber is pumped directly through the grating which can be made to have a transmission of 0.80 or better at the pump wavelength. In this case a fiber splitter is introduced in the cavity between the erbium fiber and the multiple quantum well absorber to serve as a fiber based output coupler. The output into free space can be taken through the partially transmitting absorber as before. As in the first case, the coupling ratio can be varied by changing the splitting ratio or the reflectivity of the saturable absorber.

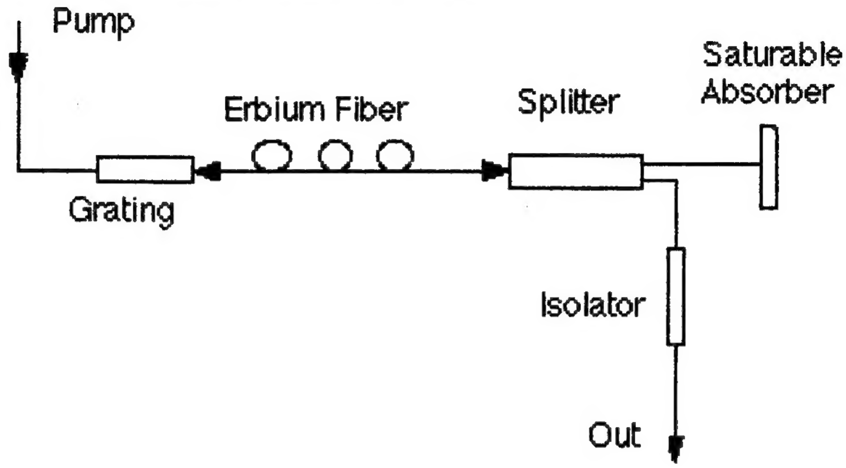

Fig. 2. Laser cavity pumped through grating.

An important and unique feature of both cavity designs is the method used to couple light in the cavity into the saturable absorber. In lasers operating at DC powers of a few mW. the cavity radiation must be focused onto a small area of the absorber to maintain the high intensities needed to saturate the absorber. For the absorbers used in our case this means areas of about 10 μm^2. We achieve this by butting the cleaved output end of the erbium fiber against the surface of the quantum well absorber. In this way sufficiently high intensities are obtained without the need for additional optical elements in the cavity which, even if coated to reduce reflections, would not only introduce losses but produce reflections in the cavity which greatly increase the pump power needed to start mode locked operation. Butt coupling the fiber against the absorber also permits the absorber to be attached to the fiber with an optical quality Uv cured epoxy. This stabilizes the position of the fiber on the absorber and thus greatly enhances the overall stability of the laser. It also results in a monolithic cavity design which requires only a very small chip of the absorber rigidly incorporated into the cavity. This important design feature means that more than one hundred lasers can be constructed from one square centimeter of absorber.

2.2 Grating Design and Fabrication

As noted above, the fiber gratings used as one reflector in the linear cavity designs described above determine the mean operating wavelength of the laser within its gain curve. Since there are two emission bands associated with laser action in erbium fiber

these lasers basically have two regions of operation, one centered around 1.53 mm and the other around 1.55 μm. Since absorption loss in erbium fiber is lower in the longer wavelength region, it was found that the most efficient mode locked operation was obtained around 1.556 μm, and the gratings used were designed to have their peak transmission near this wavelength.

In the case where the grating was used as the output coupler, two values of the transmission were tried. These were nominally 0.50 and 0.90. The lower transmission resulted in a substantial increase in output power reflecting the high gain which is a characteristic of erbium fiber, however the grating transmission for maximum output power was not determined in this investigation.

A requirement for the reflectors used in mode locked lasers is that their band width, or region of maximum reflectivity, be larger than the spectral band width needed for a given pulse duration. For a laser designed to operate with a pulse duration of 10 ps. at a wavelength of 1.55 μm this translates into a spectral band width of approximately 0.5 nm. Gratings with the required transmission and band pass are relatively easy to manufacture and, in fact, are are commercially available. Those used in this project were supplied by Dr. Kent Hill of the Communications Research Center, Ottawa, Canada and Professor Turan Erdogen of The Institute of Optics, University of Rochester, Rochester, New York. The characteristics of two of these gratings are shown in Figs. 3 and 4. It should be noted that in no case did the band width of the gratings limit the pulse duration of the laser.

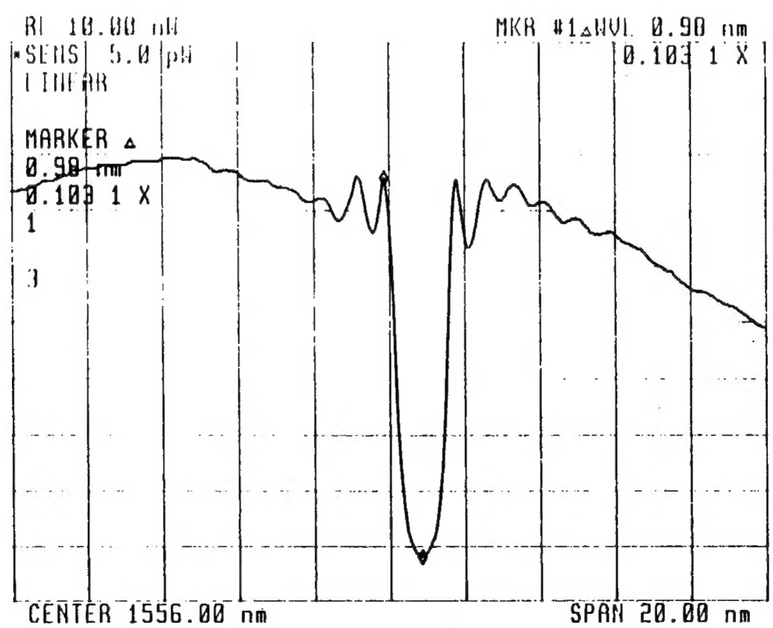

Fig. 3. Grating AF-4B supplied by Dr. Kent Hill,CRC.

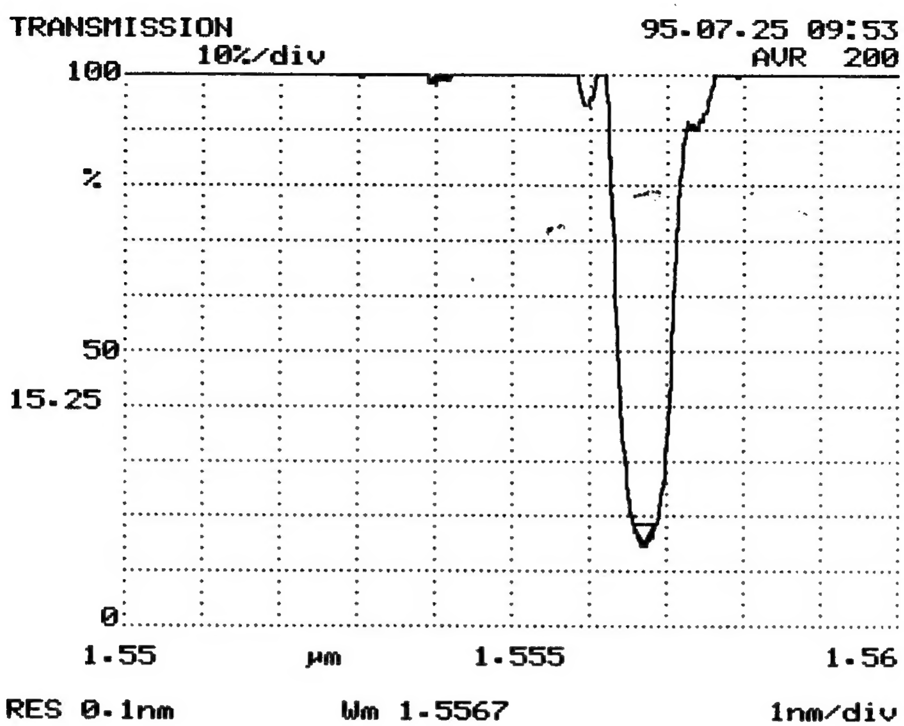

Fig. 4. Grating T950726A supplied by Professor Turan Erdogen,

2.3 Pump Laser Design

The lasers developed during the course of this project were pumped at 977 nm. with a pigtailed semiconductor laser purchased from the Seastar Corporation. This laser produced a maximum of 70 mW. of optical power in a single mode fiber at a pump current of about 200 mA. The operating characteristics of this laser are shown in Fig. 5 and its output spectrum in Fig. 6. The spectrum contain only few temporal modes and the output wavelength could be temperature tuned to match the 977 pump band of the erbium fiber. The temperature which produced the most efficient output spectrum was 17 ^{o}C.

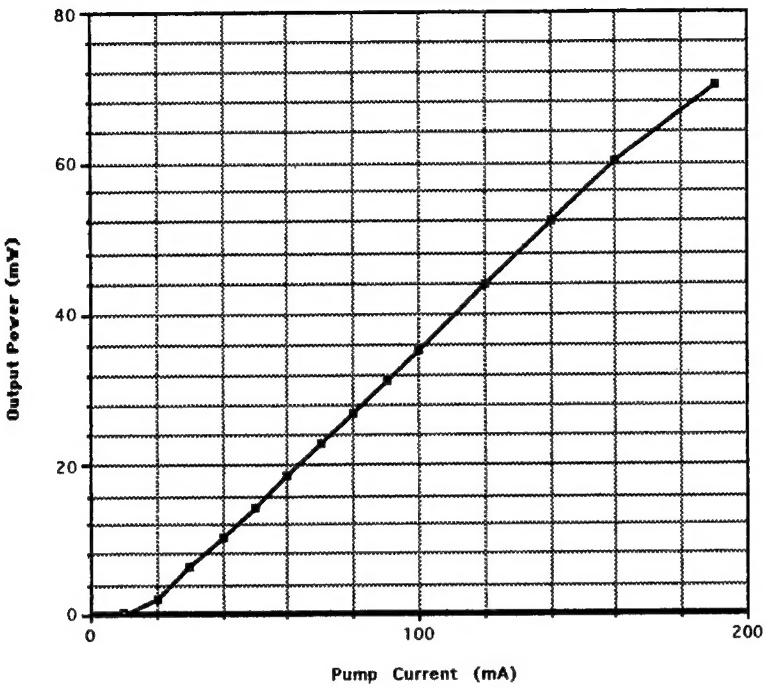

Fig. 5. Operating characteristics of the pump laser.

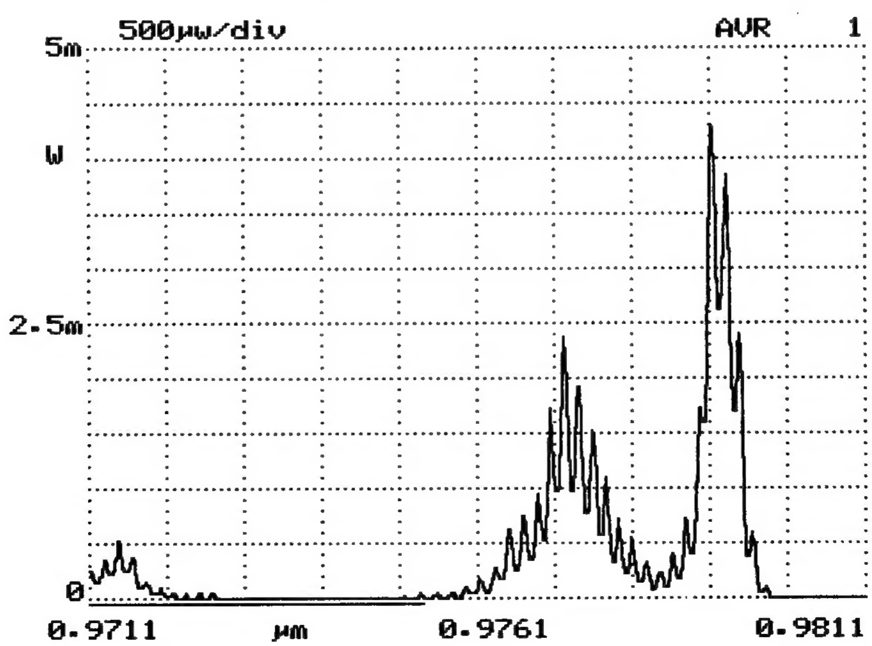

Fig. 6. Spectrum of the pump laser.

2.4 Quantum Well Saturable Absorber

Saturable absorbers constructed of semiconductor quantum wells have been successfully employed in mode locking Ti:sapphire lasers. In these applications, the saturable absorbing quantum well sample is positioned inside the laser cavity and passively, *i.e.* without electrical or optical control, causes the laser to mode lock. It was the aim of this project to develop semiconductor quantum wells suitable for mode locking Er^{3+} fiber lasers. To this end, several quantum well structures were designed in collaboration with Professor Gary Wicks at The Institute of Optics, University of Rochester and grown by him using molecular beam epitaxy. Both the linear or low intensity absorption spectra and fluorescence efficiency of the samples were measured at Rochester. They were then evaluated at Rome Laboratories to determine optimum compositions and growth parameters. Nonlinear absorption spectra and fluorescence spectra were also measured at Rome Laboratories using a unique tunable mode locked Cr^{3+}:YAG laser developed there.

2.4.1 Materials Selection

Ti:sapphire lasers operate in the $\lambda \sim 800$ nm range. The appropriate semiconductor material system for saturable absorption at 800 nm is AlGaAs/GaAs. The present application requires saturable absorption at $\lambda \sim 1.55$ μm, which necessitates a different choice of semiconductor materials. There are two reasonably well developed semiconductor material systems for construction of quantum wells with near band edge (saturable) absorption at 1.55 μm, $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ and $InP/Ga_{0.47}In_{0.53}As$. The molecular beam epitaxy (MBE) system used for the growth of the semiconductor samples for this project has the capability of growing both of these 1.55 μm material systems. The former system is easier to grow since it contains only a single group V element, arsenic and it was emphasized in the proposed task. Additionally, quantum wells consisting of the backup material system $InP/Ga_{0.47}In_{0.53}As$, were constructed and evaluated.

2.4.2. Summary of Sample Characteristics and Growth Parameters

During the course of this project, a total of 9 samples were grown by molecular beam epitaxy (MBE). All samples consisted of a 50 periods of 100 Å wells and 100 Å barrier layers deposited on InP substrates. The total thickness of the the layers (50 x [100 Å + 100 Å]) is 1 μm; the nominal substrate thickness is 500 μm. In all cases the well material was $Ga_{0.47}In_{0.53}As$. Most of the samples had InP barriers, but two had $Al_{0.48}In_{0.52}As$ barriers. The characteristics of the samples is summarized in Table 1.

sample no.	structure	growth temperature (°C)	absorption edge wavelength (nm)	exciton structure	comments
1298	AlInAs/GaInAs	490	-		unsuccessful growth
1303	AlInAs/GaInAs	490	-		
1305	AlInAs/GaInAs	490	1620	none	grown like 1303, except with higher arsenic flux
1442	InP/GaInAs	430			
1444	InP/GaInAs	430	~1590	very weak	grown like 1442, except shorter phosphorus growth stop
1461	AlInAs/GaInAs	430	1607	none	
1544	AlInAs/GaInAs	520	1645	strong	
1580	AlInAs/GaInAs	445	1624	strong	
1590	AlInAs/GaInAs	405	1617	moderate	grown like 1580, except lower growth temperature

Table 1. Summary of growth parameters and optical transmission of samples grown for this project

2.4.3 Linear Transmission Spectra

The cw linear optical transmission spectrum of six of the samples were measured with a commercial spectrophotometer. The absorption edge was estimated by visual inspection of the data, and is listed in table 1. Also listed in table is the qualitative strength of the exciton features in the transmission spectra. These six transmission spectra are shown in figures 7 - 12.

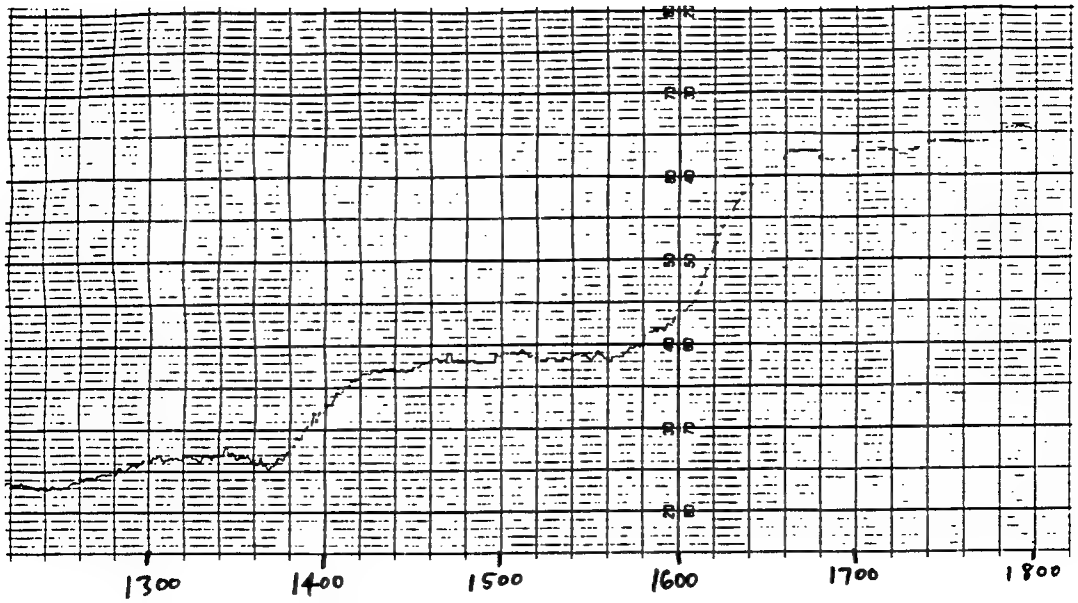

Fig. 7. Transmissivity (arb. units) vs wavelength (nm) for sample #1305.

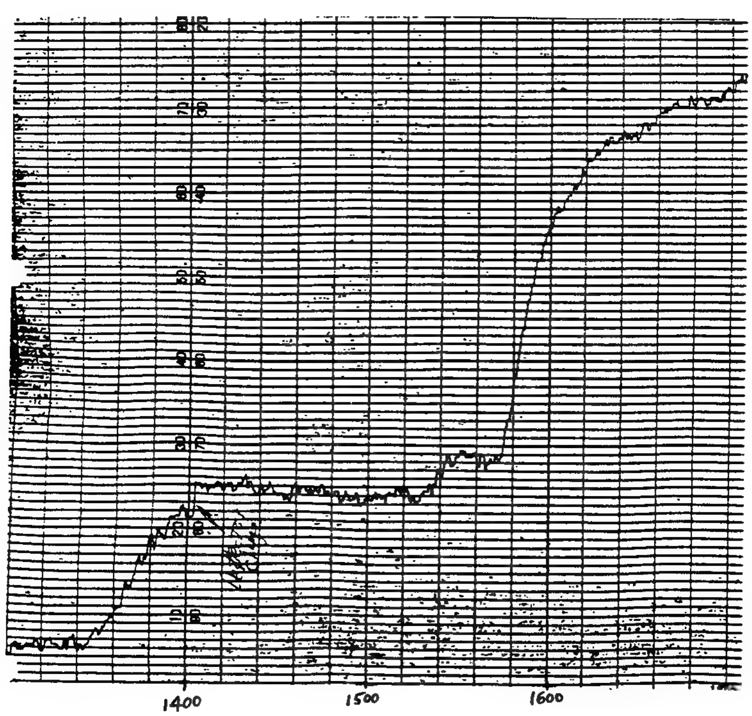

Fig. 8. Transmissivity (arb. units) vs wavelength (nm) for sample #1444

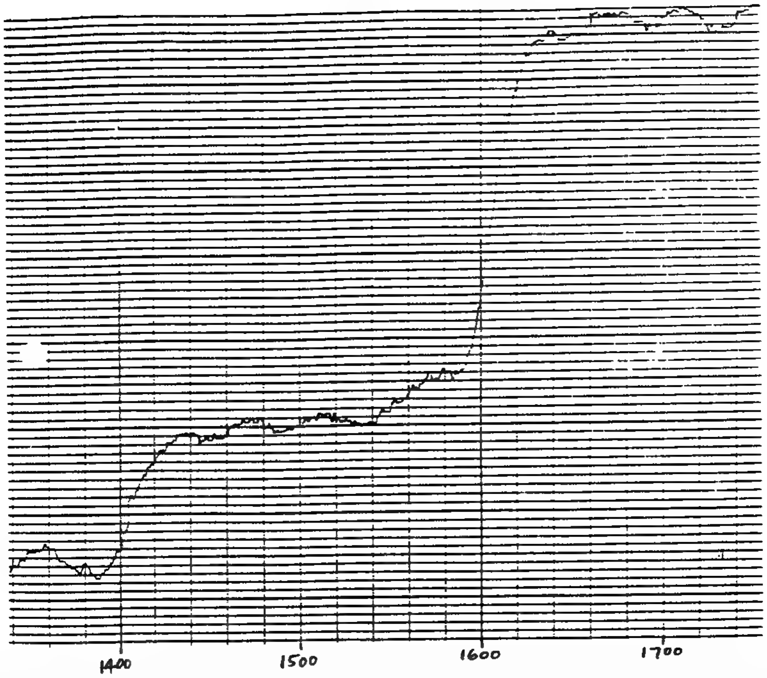

Fig. 9. Transmissivity (arb. units) vs wavelength (nm) for sample #1461

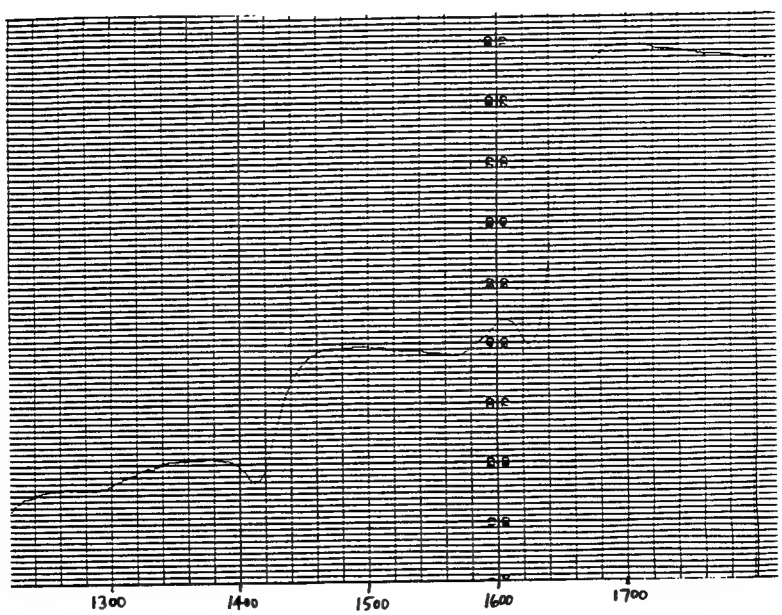

Fig 10. Transmissivity (arb. units) vs wavelength (nm) for sample # 1544

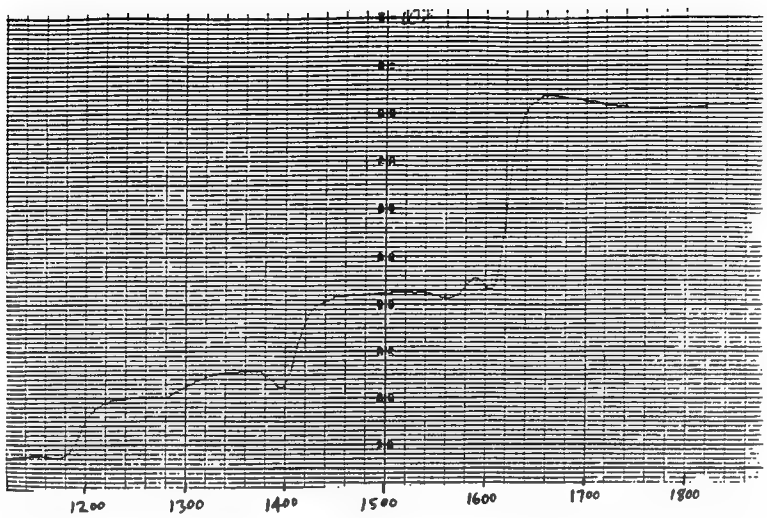

Fig. 11. Transmissivity (arb. units) vs wavelength (nm) for sample #1580

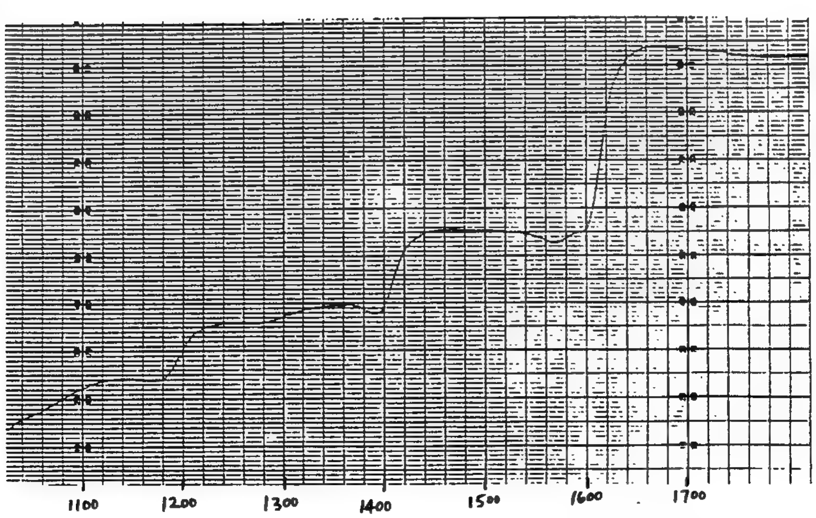

Fig 12. Transmissivity (arb. units) vs wavelength (nm) for sample #1590

2.4.4 Non Linear Transmission Spectra.

The non linear or high intensity transmission spectra of three saturable absorbers were obtained at Rome laboratories by Mike Hayduk. These measurements were made at two wave lengths which correspond to the two peaks in the gain curve for erbium fiber lasers, namely 1.53 μm and 1.55 μm. The spectra are shown in Figs. 13 through 18. In these figures the horizontal axis gives the incident intensity on the sample. The values of intensity used were chosen to simulate the actual intensities which occur when the saturable absorber is placed in the laser cavity. In DC operation, the light intensity in the cavity at the absorber was about 1.0 kW/cm^2 while peak intensities of about 1.0 x 10^4 kW/cm^2 occurred during mode locked operation. At low incident intensities, the transmission shown for all samples agrees well with the results of the low power measurements given in Figs. 8 - 14. All samples showed a threshold for non linear transmission between 1.0 kW/cm^2 and 10.0 kW/cm^2. Above 10.0kW/cm2 the transmission was saturated. Values of the threshold, the shape of the non linear transmission curve, and the saturated transmission were different for each sample and wavelength, but definite trends are hard to see in this raw data.

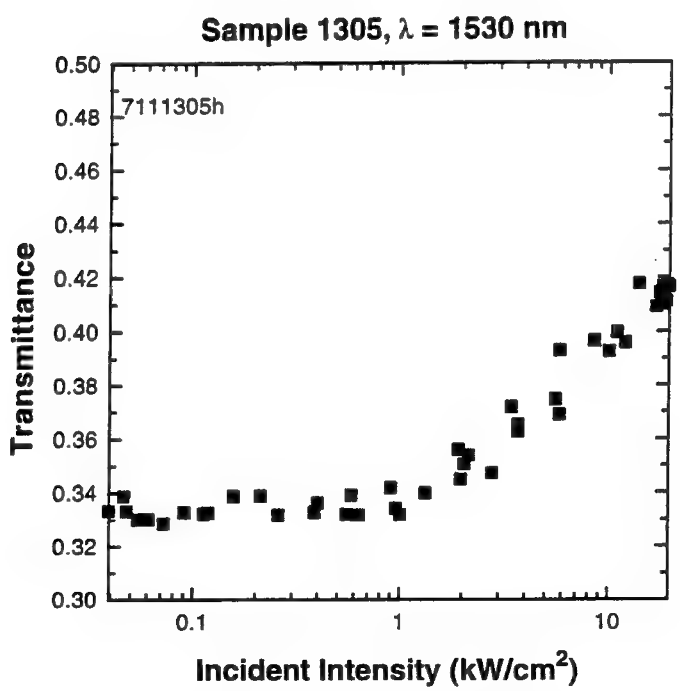

Fig. 13. The non linear transmission at 1.53 μm vs intensity for sample #1305

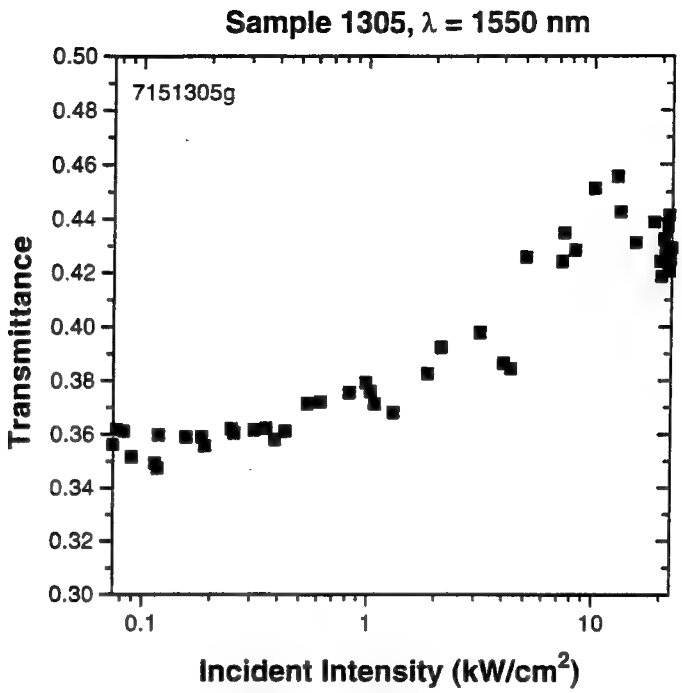

Fig. 14. The non linear transmission at 1.55 μm vs intensity for sample #1305

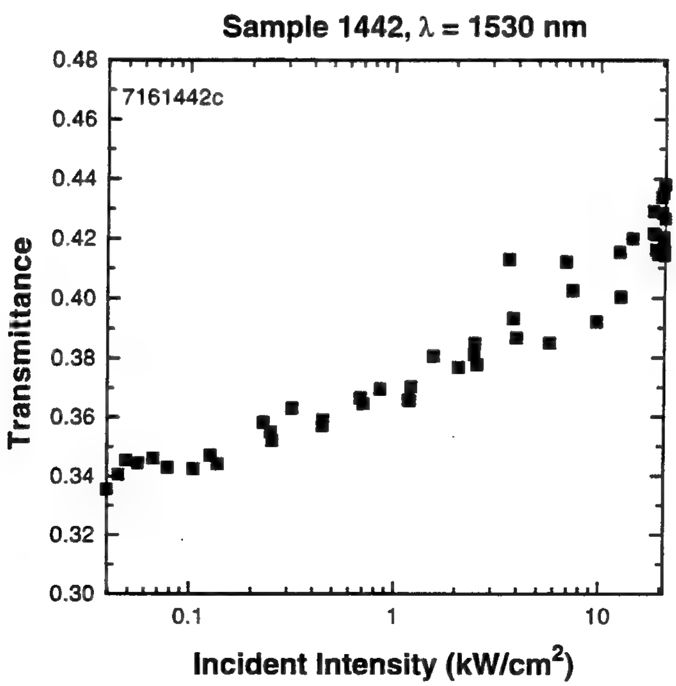

Fig. 15. The non linear transmission at 1.53 μm vs intensity for sample # 1442

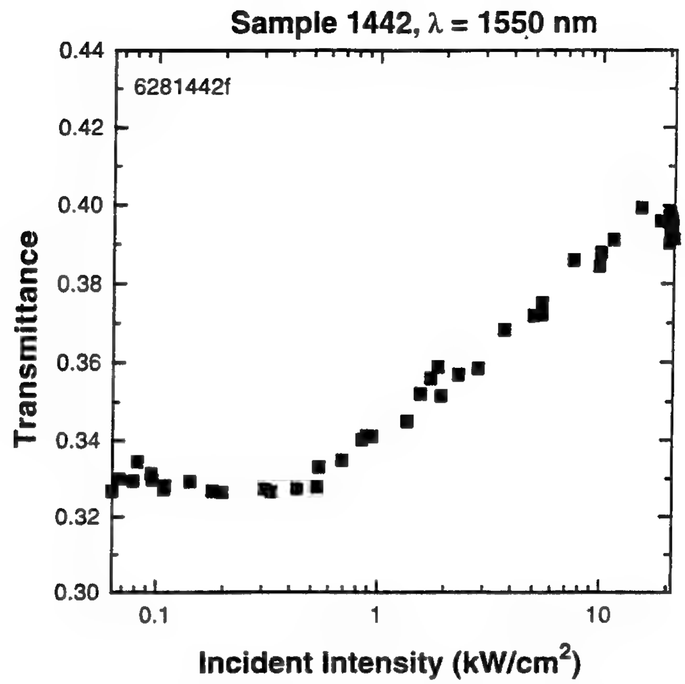

Fig. 16. The non linear transmission at 1.55 μm vs intensity for sample # 1442

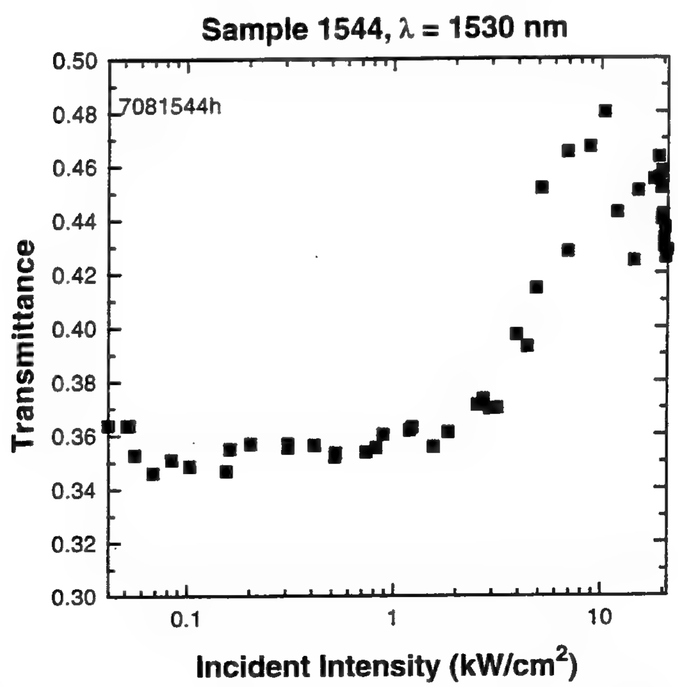

Fig. 17. The non linear transmission at 1.53 μm vs intensity for sample # 1544

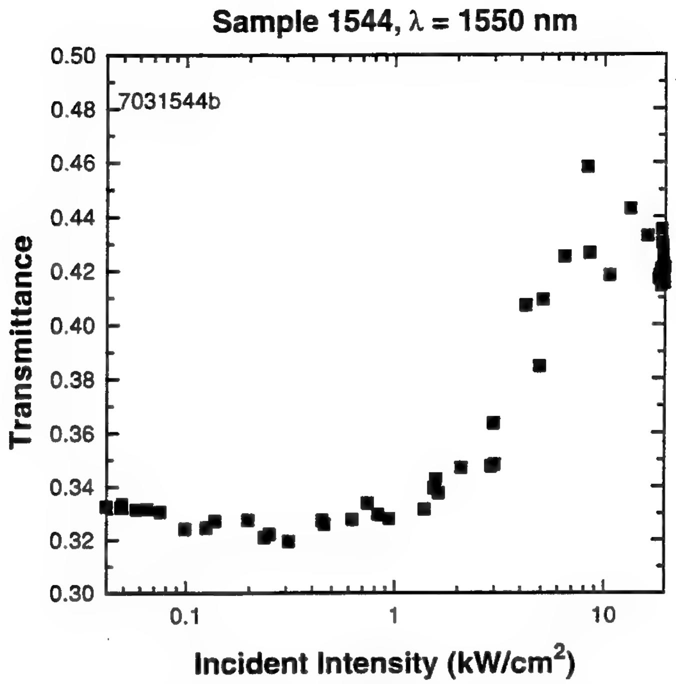

Fig. 18.The non linear transmission at 1.55 μm vs intensity for sample # 1544.

2.4.5 Photo luminescence Spectra

Room temperature photo luminescence spectra were measured on three samples: 1305, 1442 and 1590, each excited with the same wavelength and with the same input power. The spectra are shown in Fig. 19. They were obtained by exciting the multiple quantum well structures with light of photon energy well above the band edge of the host material.The luminescence shown can thus be associated with the recombination of carriers at the bound states of the quantum wells. If the luminescence decay rate consists of both radiative and non radiative processes, the relative intensity of the photo luminescence can be correlated with the decay time of carriers in each sample. An interpretation of the data shown in Fig. 21 is that the importance of non radiative process increases as we go from sample 1590 to sample 1305 and hence the decay rate increases, shortening the lifetime of the carriers. A decrease in carrier lifetime of almost a factor of five is indicated by this data. Since the saturation flux depends reciprocally on the decay rate, sample 1305 should have the highest saturation flux of the three samples studied. It is not obvious that this prediction is born out by the non linear transmission data shown in Figs. 15 - 20. However it is clear that the photo luminescence data provide the clearest distinction between the three samples. Since it was found that sample 1305 had the lowest threshold for mode locking, and produced the shortest pulses, this data provides some indication of one parameter that might be monitored during the MBE growth process to optimize performance.

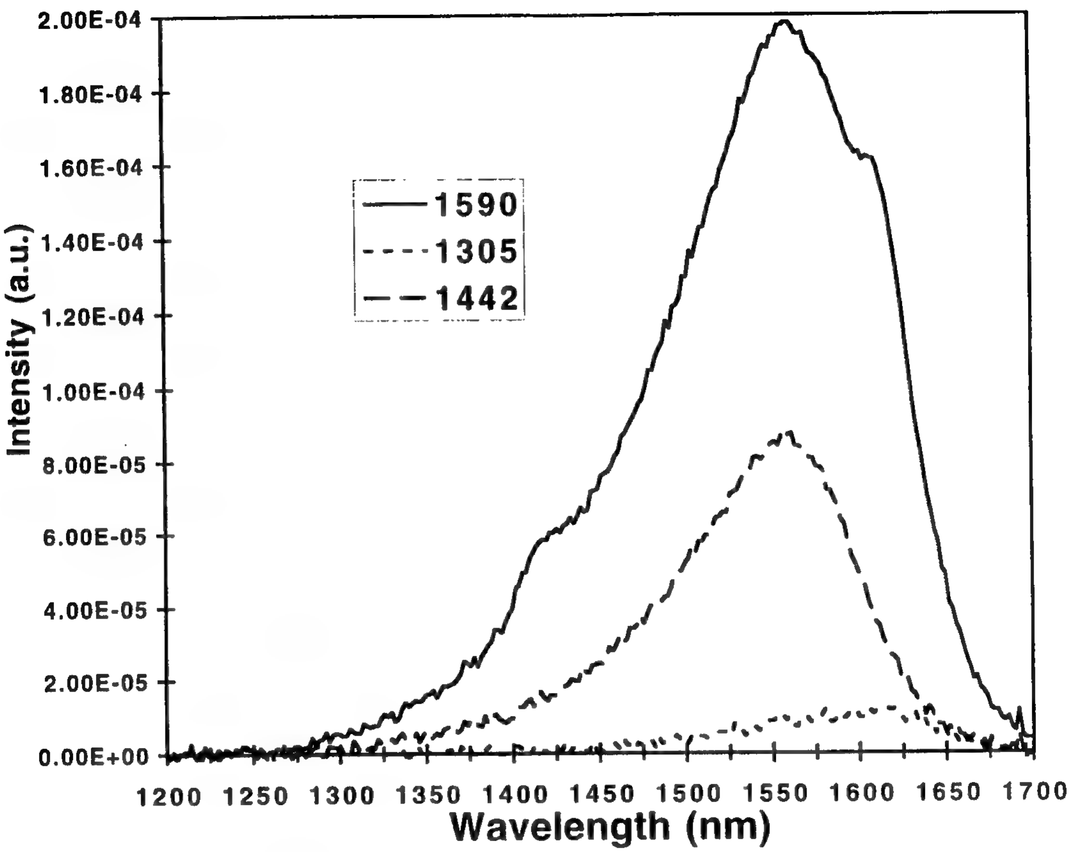

Fig 19. Relative photo luminescence spectra for three saturable absorbers

2.4.6 Mode Locked Operation

The saturable absorbers described above were used to mode lock the laser cavity shown in Fig. 1. Two slightly different gratings were used in these experiments. the transmission of the two gratings vs. wavelength is shown in Figs. 3 and 4. The most notable difference between the two was the the band pass or full width at half maximum of the transmission band. For grating AF-4B this was 1.6 nm, while for grating T950726A it was 0.74 nm. The second grating was found to mode lock samples 1305, 1442, and 1461, while only sample 1305 could mode lock the cavity with the first grating. the temporal width of the output pulses for each sample, obtained with grating T950726A, differed. Sample 1305 always produced the shortest pulses. It was also found that the threshold for mode locking was lowest for sample 1305. It was found that mode locking was dependent on the position of the output fiber on the surface of the saturable absorber. As the distance from the saturable absorber was changed, maxima and minima in the out put power of the laser and the threshold for

mode locking were observed. These quantities oscillated in a manner suggestive of interference effects between the end of the fiber and the surface of the absorber. The output power and threshold also appeared to be dependent on the lateral position of the fiber. This result is subject to some uncertainty because it was hard to maintain a constant distance from the absorber while the lateral position was changed. Temporal pulse widths and spectral widths for the samples so far tested are shown in Table 2.

Sample	Grating	Pulse width	Spectral width	Product
1305	T950726A	8 ps	0.34 nm	0.33
1442	T950726A	30	0.08	0.24
1444	T950726A	33	0.11	0.36
1461	T950726A	30	0.09	0.26
1305	AF-4B	8	0.38	0.37
1442	AF-4B	did not ml		
1444	AF-4B	did not ml		
1461	AF-4B	did not ml		

Table 2. Temporal pulse widths and spectral widths for several samples

2.5 Mode Locked Laser Assembly

The results described above were used to construct a rugged, compact, mode locked fiber laser utilizing the cavity design shown in Fig. 1. In this laser a piece of saturable absorber of about 1 mm^2 area was attached to the end of the cavity using UV curable epoxy. This procedure resulted in a laser which was self starting and very stable. The laser was enclosed in a 2x3x5 aluminum box with an FC/PC connector as the out put port. It was operated for approximately one month without noticeable deterioration in its output characteristics. The out put spectrum and auto correlation traces for this laser are shown in Figs. 20 and 21. This data indicates a time - bandwidth product of approximately 0.3, close to the value of 0.33 expected for transform limited operation with a hyperbolic secant squared pulse shape.

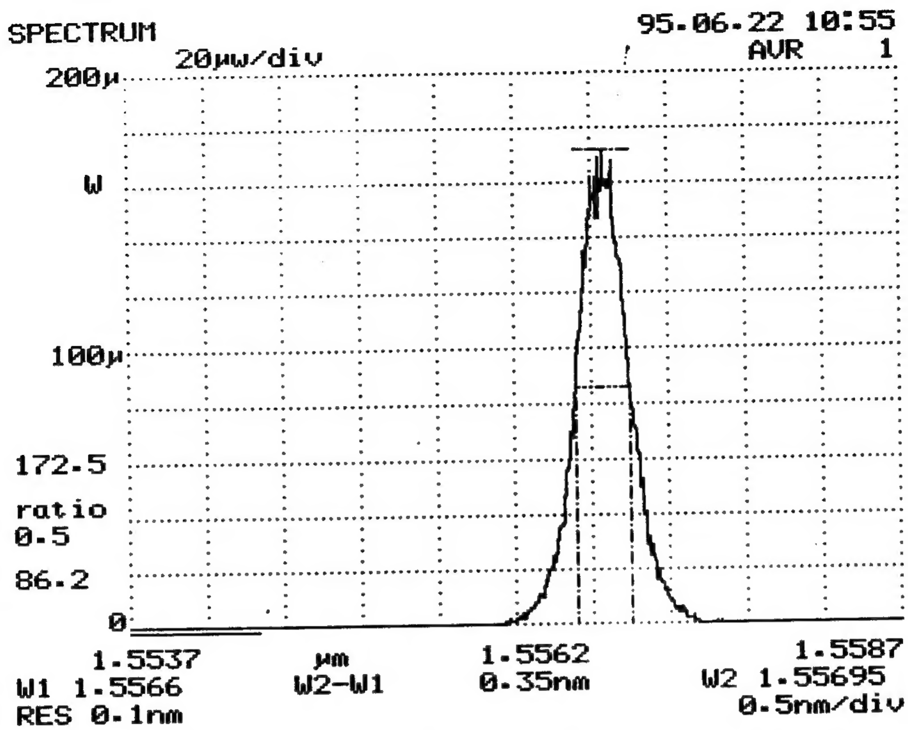

Fig 20. Output spectrum of the completed laser.

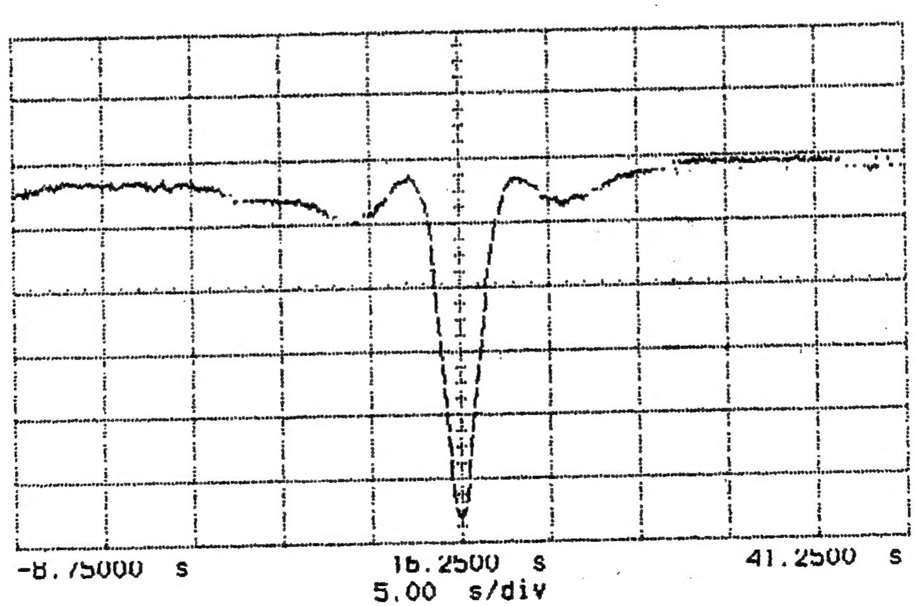

Fig. 21. Auto correlation trace for completed laser. The corresponding pulse width was approximately 8 ps.

3.0 Discussion

One important obstacle to the construction of a monolithic all fiber mode locked laser has been the incorporation of the mode locker into the laser cavity. In the past coupling light into a saturable absorber in a fiber laser has involved the introduction of optical elements such as microscope objectives into the cavity to focus radiation and obtain the high intensities needed to achieve saturation. These optical elements increase the complexity, size, and weight of the laser and because of reflections and absorption introduce instabilities and raise the pump power threshold for mode locking. We have solved this problem in a simple way by attaching a semiconductor saturable absorber directly onto the end of the fiber cavity with optical grade epoxy. The result is a transform limited mode locked laser which is self starting with minimal pump power. The laser can be operated with readily available pig tailed semiconductor laser diodes as the pump and they produce pulses of approximately 10 ps. duration and peak powers of approximately 10 W. Because only a very small piece of saturable absorber is needed, as many as 100 lasers can be constructed from a 1.0 cm^2 piece of saturable absorber.

A problem yet to be solved is the reproducible growth of optimal material for the saturable absorber used in our laser. It was shown in our studies that the quantum well absorber that has the lowest threshold and shortest pulse duration is characterized by a relatively short fluorescent decay time. However, the MBE growth conditions which determine this decay time have as yet not been established. It is suspected that rapid carrier recombination is promoted either by disorder in the GaAs lattice structure or by some common impurity such as oxygen. Disorder can be controlled by the temperature of the substrate during growth and the presence of an impurity by chemical analysis or deliberate doping using a technique such as ion implantation. All these approaches should be tried in future studies.

Another important area for future investigation is the interaction between the properties of the grating used as a reflector in the cavity designs described above and the multiple quantum well structures used as the saturable absorber. Our data indicates that the proper grating can mode lock a range of saturable absorbers with quite different characteristics, while another works only with one material. Clearly the optimum laser will be obtained with the proper match of grating to material. It is not clear whether it is the grating wavelength or band pass that determines this behavior. Since fiber gratings with controlled properties are readily available, a study which determines the relative importance of these factors would not be difficult to undertake.

Finally, a more advanced quantum well structure, one that is electrically controllable, should be examined. It is known that an external voltage applied to a quantum well structure shifts quantum well absorption spectra and decreases the exciton oscillator strength via the quantum confined Stark effect and ways of applying this voltage have already been developed.[5] Synchronizing voltage pulses on the quantum well structure with the mode locked pulses of the laser could greatly reduce timing jitter in

the output pulses of the laser. Driving the mode locker at a high harmonic of the cavity frequency would increase the repetition rate of the mode locked pulses and enhance the usefulness of the laser in communications applications. A secondary use of these electrically controllable quantum well structures would be in voltage-controllable wavelength tuning of the laser.

4.0 References

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